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The Reality of the Greenhouse Effect

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Abstract

The Earth's surface absorbs solar radiation, to which the atmosphere is mostly transparent, and re-emits infrared radiation that is absorbed primarily by carbon dioxide and water vapor. Without the consequent warming, or "greenhouse" effect, the Earth's mean surface temperature of 15°C would be well below freezing.

Changes in the concentration of CO_2 and other greenhouse gases can perturb the present climate. Theoretical models constructed to generate quantitative estimates of these changes suggest that a doubling of the CO_2 concentration could raise global-average temperatures by 1.5 to 4.5°C. Global temperatures appear to have risen about 0.5°C over the past hundred years, in part probably due to the 25% rise in CO_2 concentration. There are important questions, however, regarding the rate and history of the warming and the spatial pattern of the changes.

The projected climatic changes could induce significant societal impacts, especially if society is viewed as unresponsive. Sea level rise, reduced water resources, and stressed

agricultural systems may be the most important consequences, but uncertainties in the estimated climatic effects and the long lead time make assessment difficult. Developing and evaluating options for slowing the rate and magnitude of and adapting to the projected changes require accelerated research.

Introduction

"Greenhouse effect" is the term used to describe the ability of the atmosphere to warm the surface by absorption and downward reradiation of a large fraction of the infrared radiation emitted from the Earth's surface. Were it not for the greenhouse effect, the Earth's climate would be, on average, cold, icy, and unfit for life. The climates of the nearby planets demonstrate that the greenhouse effect is real and that different concentrations of infrared-absorbing gases such as carbon dioxide, methane, nitrous oxide and chlorofluorocarbons, would lead to a different climate.

The crucial question, however, is not what the sign of the effect might be — it is certainly positive. Instead we need answers to a number of more detailed and more relevant questions about the potential climatic consequences of increasing concentrations of CO_2 and other greenhouse gases.

1. How much warmer will the world become? What other changes could occur and are they large compared to natural variability?
2. Where could the changes occur?
3. How rapidly will the changes occur?
4. What is the environment and societal significance of the climatic changes?
5. Can and should, anything be done now about the projected climatic changes? And when must various actions be taken?

These questions are only an initial set of questions; there are many more. For all of these questions and more, it is also essential to understand how certain we are about our answers. This set of questions, however, is a challenging start.

I want to emphasize that this analysis, particularly my comments on societal significance, represent my personal interpretation, and not necessarily the views of the Lawrence Livermore National Laboratory or the Department of Energy.

Background

As background for addressing these questions, it is necessary to understand some aspects regarding the methods, tools, and understanding that scientists invoke in trying to answer these questions. We know from studies of past climates that the climate can change. During the Cretaceous period from 65 to 140 million years ago — a particularly important time in the path leading to this Congress — the climate was considerably warmer, perhaps by 10°C on a global average, and was especially warmer in polar latitudes, a fact that currently defies explanation. Over the last million years, cycles of glacial advances and retreat have dramatically altered the climate and molded surface features. Over shorter time scales, there have also been significant changes, with the distribution of wet and dry regions and soil moisture apparently having changed more significantly than temperature.

We do not know with certainty what caused these and other changes, although we have learned some important lessons:

1. The climate has changed — and presumably could change naturally in the future as well as due to human influences — perhaps in dramatic and unexpected ways. A constant climate is not guaranteed.

2. The most likely factors contributing to these changes involve alteration of the Earth's radiation balance, whether because of variations in solar radiance, changes in the Earth's orbital parameters, or changes in the atmosphere's gaseous or particulate composition (e.g., by volcanoes). While recognizing the role of radiative changes, however, we must always keep in mind that changes in ocean circulation, surface reflectivity, and, on even longer scales, in topography and the position of continents, have also contributed to climatic changes and could, along with other factors such as cloud cover, perhaps amplify or moderate changes resulting from the radiative perturbations.

Study of past climates can provide indications of how sensitive the climate is to various changes, but no appropriate and well-established analog exists for the "vast geophysical experiment" [1] that is occurring as society alters atmospheric composition. To move beyond a qualitative statement indicating that increasing concentrations of greenhouse gases will warm the climate, models of the climate must be constructed. Because of the complexity of the climate, suitable laboratory models cannot be constructed and numerical models solved by computers must be used. These models, the most sophisticated of which are called general circulation models (GCMs), are based on the fundamental physical laws governing conservation of mass, momentum, and energy. The great range of time and space scales and the many processes that need to be represented, however, require that these models incorporate many approximations. A crucial question is whether the resulting models, although still so complex that they require tens to hundreds of hours of computer time to simulate a year of atmospheric behavior, provide an adequate representation of both the present climatic conditions and the sensitivity of the climate to changes in atmospheric composition.

Two types of tests of such models are used. In the first, the accuracy of the various processes in the model are tested separately. This is possible for processes such as visible and infrared radiation, the representations of which can be tested against laboratory experiments and satellite observations, and even for atmospheric dynamics, the representation of which can be tested against the evolution of particular weather events. Comparing model predictions of the evolving weather with observations has emphasized the highly non-linear nature of the climate system, for even provided with nearly perfect observations to initialize a perfect computer model, mathematical analyses demonstrate that detailed predictions of even the large scale atmospheric behavior can be skillful (i.e., better than simply assuming the climatological or historical average conditions) for at most a few weeks; present models using real observations lose their skill in a few days, partly due to less than perfect observations and partly due to less than perfect models.

But, if models cannot predict the evolution of the weather for more than a few days in advance, then of what use are they in making predictions a century in the future?

The answer to this question is the same as for other situations where we are dealing with turbulent fluids, whether flowing over an airplane wing, around a car, or through a pipe; namely, that, although we cannot predict the details of the individual event, we may be able to use the models to predict the statistical average of many individual turbulent events. For the atmosphere, this statistical average of the weather is known as the climate. We are, therefore, trying to predict perturbations to the long-term average conditions (i.e., the climate), not to predict the detailed weather 100 years in the future.

The second way of testing models is to compare their predictions of the climate to observations. Although the degree of agreement among models differs, available models can simulate the general patterns of climate throughout the world and over the course of the year, although the quantitative detail of the model simulations is not yet adequate. Simulation of the annual cycle of climate also provides a verification that the models can simulate climatic change in response to a comparatively large change in radiative forcing. Because models necessarily contain approximations to the fundamental equations, some "tuning" of unmeasureable parameters in the models has occurred. To provide an independent test of the models, therefore, attempts are being made to simulate past periods when the climate was different, although such tests can only be definitive if we know both the causes and the changes that occurred. John Kutzbach and his colleagues at the University of Wisconsin, for example, have used climate models to demonstrate that the Earth's orbital variations over the last 18,000 years explain many aspects of the emergence from the maximum glacial conditions [2].

Climate models, the best of which are now starting to incorporate coupled treatment of the atmosphere, oceans, land surface, hydrology, and cryosphere (i.e., sea ice, land glaciers), provide the fundamental tool for making the climate projections on which all of the later conclusions regarding perturbations and impacts are based. At the present stage, available models provide a qualitative representation of the large scale climatic features, reasonably well, but they are less satisfactory in representing the detailed regional and seasonal evolution of temperature (see Figure 1) and other climate variables. The ability of the models to project changes in the year to year variability and in the frequency of occurrence of extreme events is also very limited.

How Much Warmer Could the World Become?

A traditional measure of the effect of changes in atmospheric composition on the climate is to calculate the effect on the modeled climate of a doubling of the atmosphere's CO_2 concentration above its pre-industrial level (e.g., from an assumed level of 300 to 600 parts per million by volume-ppmv), an increase that may occur by 2100. The resulting climate change is known as the equilibrium climate change, because the model results assume that a new, annual average, equilibrium climatic state is achieved; in the event of continuing emissions of greenhouse gases, however, such a state will never be achieved. Three-dimensional models including increasingly comprehensive treatments of the oceans and geography have been used for simulations made during the last ten years. National and international reviews of these modeling studies [3, 4, 5] have concluded that the global average climate is likely to warm by 1.5 to 4.5°C in response to a doubling of the CO_2 concentration. The most recent simulations tend to be in the upper half of this range as a result of the water vapor, sea-ice, and cloud feedback processes that amplify the climate's response to the changes in radiative forcing caused by the CO_2 increase alone. For example, water vapor feedback results because warmer temperatures increase the amount of water vapor in the atmosphere, leading to further warming, and even more water vapor in the atmosphere. Significant uncertainties remain in these estimates, however. Not only do the model results differ in important ways from each other, but there is not yet convincing evidence that such changes are appearing in the observational record. Thus, much more research is needed to determine whether stabilizing feedback processes may have been omitted from the current versions of the climate models.

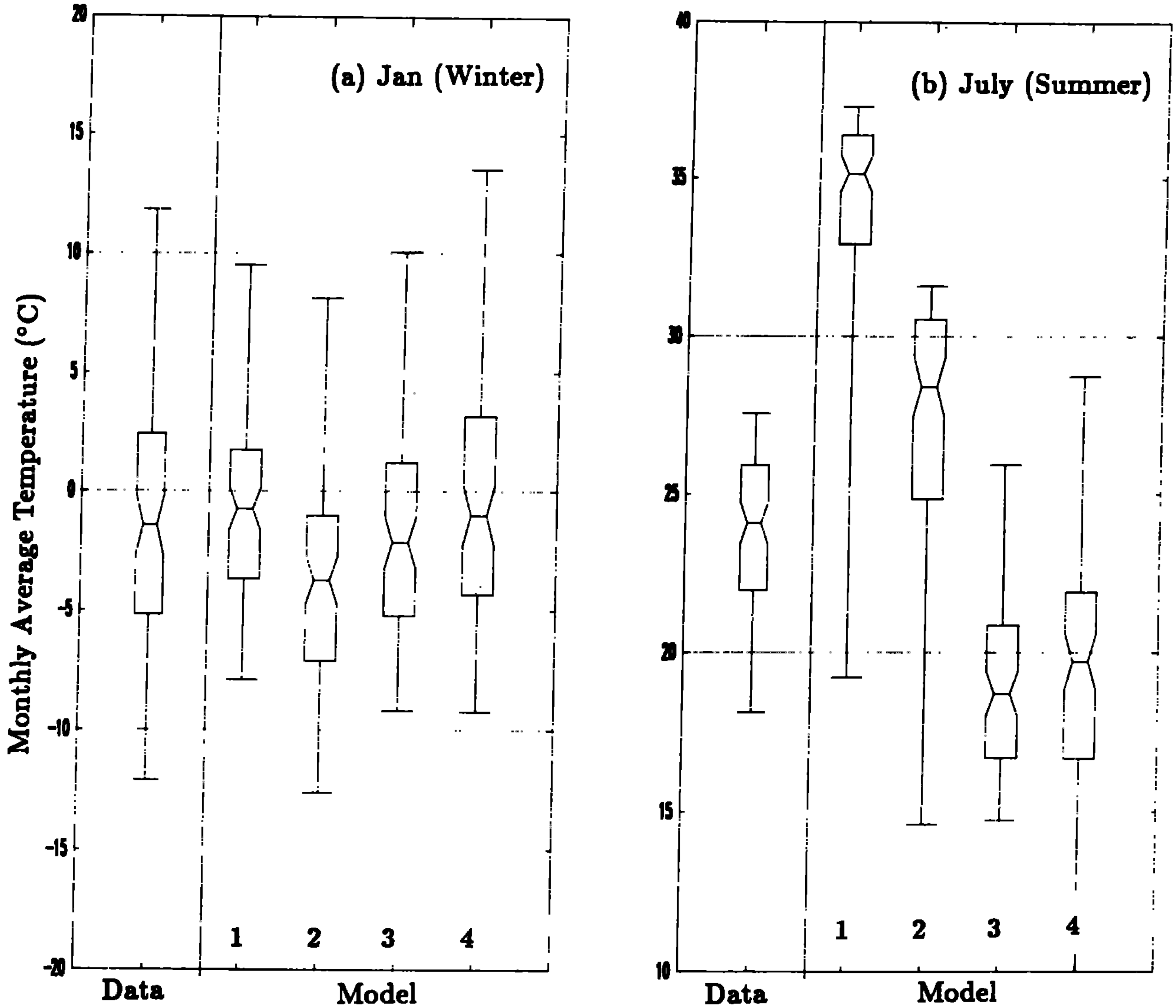

Figure 1: Box plot comparison of observed temperatures over the United States with the predicted surface air temperatures from four general circulation models (GCM) being used by U.S. researchers for (a) January or winter months, and (b) July or summer months. Model results and observations have been converted to a common grid at 90 points over the U.S. In the box plot representation, the 5 horizontal levels denote the quartiles of the data, from the top: maximum, 75%, median, 25%, and minimum, with the central box containing one-half of the data values. The notch about the median approximates the 95% confidence limits on its value, assuming normality.

Over the past few years, simulations have also been done of the potential effects of increased concentrations of other radiatively active gases. These gases, often referred to as trace gases, trap infrared radiation themselves, but also can chemically modify atmospheric chemistry, particularly the ozone concentration, in ways that can further trap the outgoing infrared radiation. Together, the chemical and climatic effects of these gases could enhance the radiative effect of the doubled CO_2 concentration by 50–100% [6, 7]. If the climatic response is linear in its response to forcing, these gases would increase the warming by an equal percentage. We know that the sea-ice effect will not be linear because the sea ice would eventually disappear, but we do not yet adequately understand the dependence of the climate's sensitivity to combined increases of CO_2 and trace gas concentrations.

Where Would the Changes Occur?

Most of the model simulations project that the warming would be largest in high latitudes, where changes in snow cover and sea ice extent could lead to warmings of 10–15°C in the transition seasons (i.e., the fall and spring periods). That is, at these high latitudes, the warm season would become longer and the cold season shorter — but the temperatures themselves during each of these seasons would be only a few degrees warmer. In low latitudes, most models project a warming of about 2°C from a doubling of the CO_2 concentration, with significantly increased evaporation from the oceans limiting the temperature rise. One model, however, suggests that the increased convective activity in the tropics may lead to increased amounts of high altitude clouds, which would tend to act like greenhouse gases and further raise the temperatures. (Low altitude clouds, conversely, have a larger effect on solar radiation than on infrared radiation, so an increase in low altitude clouds would tend to cool the climate.) Although warming in low latitudes may be less than at higher latitudes, even modest warmings in low latitudes can be important.

In middle latitudes, the few degree warming would be more uniform through the seasons, probably lengthening the frost-free growing season and increasing the frequency of very warm days in the summer. Figure 2 shows the estimated temperature increases at grid points over the United States as estimated by three general circulation models used in the U.S. Agreement varies with season, the large difference for model 2 in the summer being a result of the drying out of much of the region.

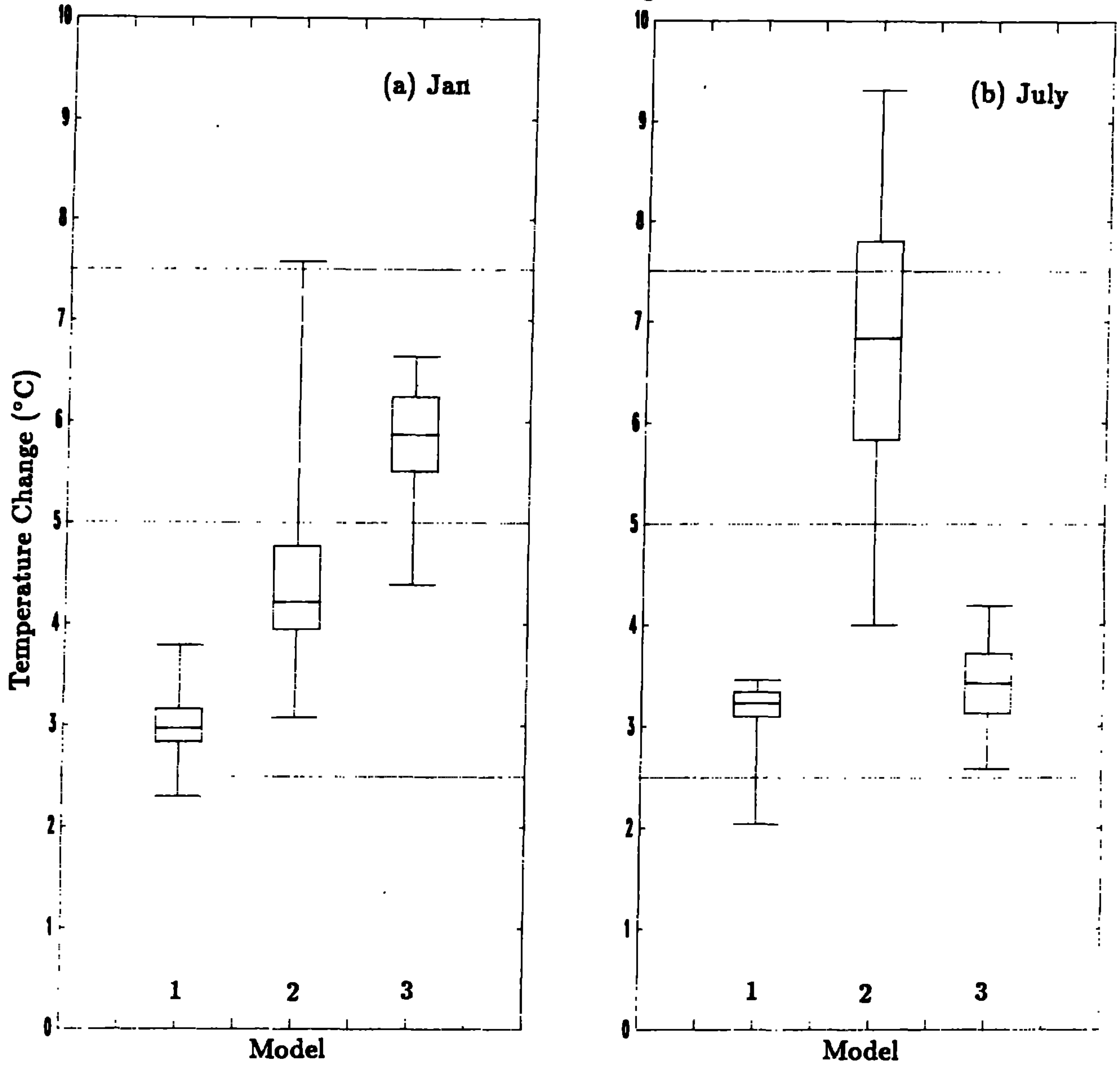

Figure 2: Box plot comparison of the predicted change in monthly average surface air temperature from a doubling of the CO_2 concentration as estimated by three general circulation models at 90 points over the U.S. for (a) January or winter months, and (b) July or summer months.

Of perhaps more economic importance than temperature changes, there would also likely be changes in the precipitation and amounts of soil moisture and runoff. There is considerable disagreement between the projections of such changes made by the different models, and the results must now be viewed as uncertain because of limitations in treatment of important physical processes. There are some indications of increased precipitation and soil moisture during the winter, but also that each winter's accumulation of soil moisture may be evaporated earlier in the year, making for drier conditions in late summer. In addition, if there is lessened snow accumulation in the mountains, water availability for agriculture, industry, energy, and other resources may become limited, and soil conservation (due to reduced soil moisture) may become an important issue.

Over the last 100 years, despite volcanic eruptions, El Niño events and other disruptions, the global-average, monthly-average temperature, as best we know it, has varied by only about 0.5°C about a running ten year average, and annual-average temperatures by somewhat less. Even over only the continental areas, the monthly average temperature has varied only about 1°C [8]. Thus, the projected global-scale changes, which would be changes in the mean about which there would continue to be warm and cool excursions, would be *unprecedented* in modern times. Figure 3 measures the significance of the predicted change of the monthly average surface air temperature at grid points over the U.S. for a doubling of the CO_2 concentration (as given in Figure 2) by dividing it by the observed standard deviation at each grid point. While the changes may not be completely unprecedented on a monthly average basis, the climatic shift is generally 2 to 3 standard deviations (indicating that the changes are well beyond the range of normal variations). Such a change could be very significant, especially given that it would persist and that the warm anomalies, with their consequent agricultural and environmental stresses, would be occurring at most locations simultaneously.

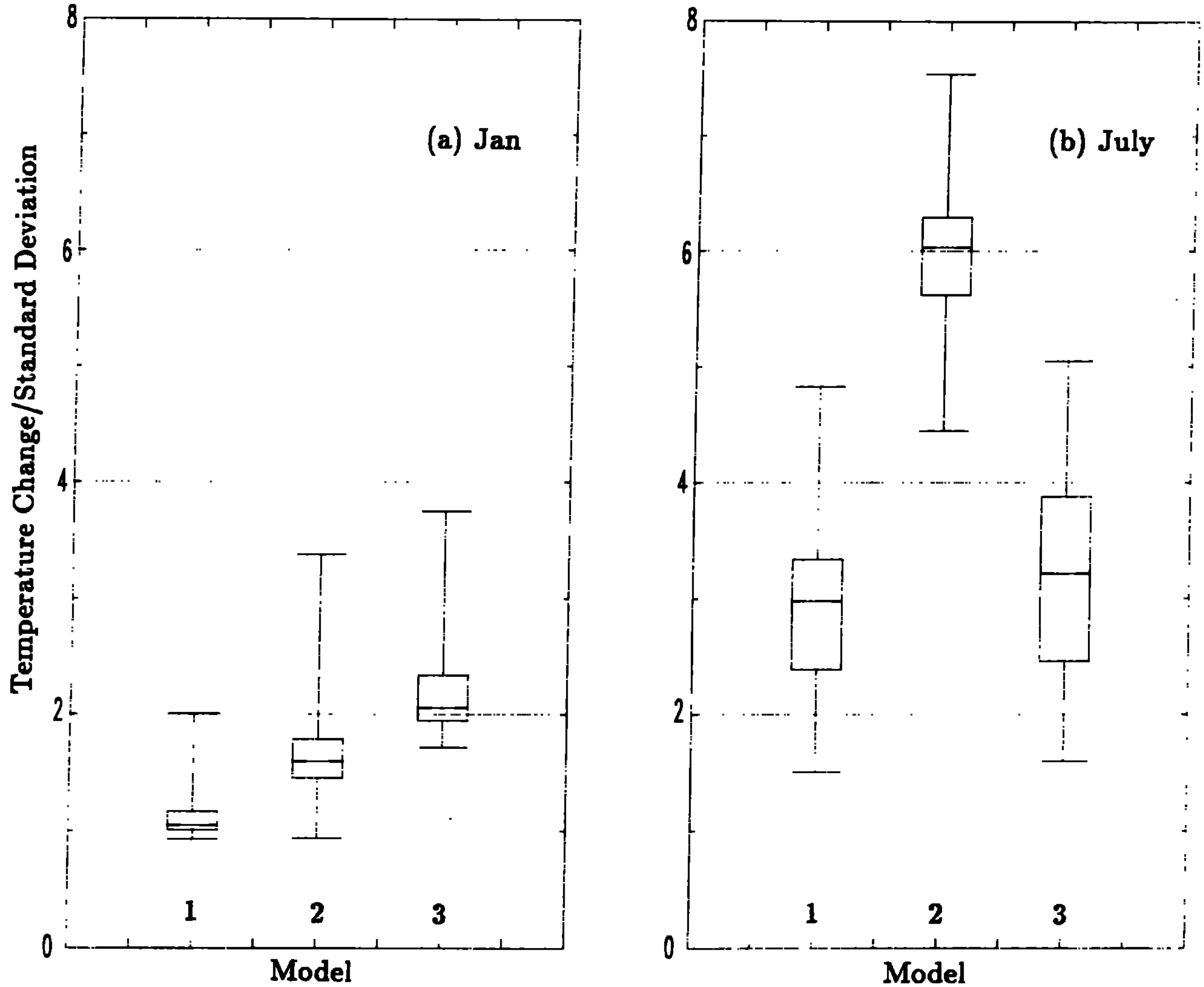

Figure 3: Box plot comparison of the ratio of the predicted change in monthly average surface air temperature from a doubling of the CO_2 concentration to the observed standard deviation of monthly average surface air temperature as estimated by three general circulation models at 90 points over the United States for (a) January or winter months, and (b) July or summer months.

How Rapidly Will the Changes Occur?

The rate of climatic change is perhaps as important as how large the equilibrium climatic change would be, because it will determine the rate at which impacts are felt and adaptations would have to occur. The rate of climate change will be controlled by two factors:

1. The rate of increase of the concentrations of CO_2 and trace gases, which are determined in turn by the sources and sinks of the various species; and

2. The rate at which the actual climate change approaches the equilibrium climate change, which is determined primarily by how rapidly heat is taken up by the oceans and by the size of the equilibrium climatic change.

The CO_2 concentration has risen from about 270–280 ppmv in the middle of the last century to about 345 ppmv in 1985 [9]. Studies of changes in carbon isotope ratios indicate that this 25% increase has been due about equally to net destruction of the biosphere (mainly from expansion of agricultural lands) and to combustion of fossil fuels. The concentration is now rising at about 1–1.5 ppmv/year (about 0.3%/yr), mainly due to fossil fuel combustion, and the rate is rising slowly as fossil fuel use increases. Although subject to many assumptions involving economics and energy policy, the concentration of CO_2 is projected to reach 600 ppmv by the middle to end of the next century.

The concentrations of trace gases are also rising. Molecule for molecule, the trace gases have a much larger radiative effect than CO_2 because of their particular infrared absorption bands. The rates of increase of the emissions of these species are also increasing more rapidly than for CO_2 emissions, with methane (CH_4) increasing at about 1%/yr (from various biogenic sources connected with increasing human population, including rice paddies, farm animals, biomass burning, etc.), chlorofluorocarbons by a few per cent per year (mainly from uses in refrigeration, air conditioning, foam-making, and industrial uses), and nitrous oxide (N_2O) by about 0.25%/yr (mainly from fossil fuel combustion and increased fertilizer use). These species also can affect atmospheric chemistry, tending to increase tropospheric and decrease stratospheric ozone concentrations, both tending to augment the greenhouse effect. Although the mass of emissions is much less than for CO_2, the increasing rates of emission of trace gases and the induced chemical changes together could induce a radiative effect equivalent to the doubling of the CO_2 concentration alone during the first half of the next century.

Thus, if the climate system could respond instantaneously to the change in its composition, the global average temperature would be expected to be about 1.5 to 4.5°C warmer in about 2050 compared to the average temperatures in the mid-19th century. Scaling logarithmically, which is how the radiative forcing varies with CO_2 concentration, the 25% CO_2 increase from 1850 to the present would be expected to have raised present global average temperatures by about 0.5 to 1.5°C, with the most recent equilibrium model results suggesting values at the upper end of this range. The modest trace gas increases over the last century would be expected to have increased this range by about 30%. Observations, however, suggest that the actual warming has been 0.5 ± 0.2°C, at the lower end of the projected range [8].

There are two plausible explanations for this discrepancy. One is that the very large heat capacity of the oceans is acting to delay the warming. The upper 50–100 m of the ocean, the temperature of which varies by several degrees over the annual cycle, can delay the warming by only a few years. If heat is being transferred to the deeper ocean, however, the warming can be slowed much more; estimates range from a few decades to more than a century [10, 11] and research is needed to resolve this uncertainty. For the upper limit of the model estimates of climate change to be consistent with observations, the oceans must be transferring heat into the deeper ocean relatively rapidly. This is a particularly important point because, if the upper climatic sensitivity (i.e., 4.5°C) is correct and the oceans are prolonging the response to equilibrium, we could already be committed to three times the warming that has occurred over the last century, even if we stop now adding any more greenhouse gases to the atmosphere.

The second possible explanation is that the present model results are overestimates and that moderating feedback mechanisms are being overlooked. A major research effort is now underway to better understand what is causing the high model sensitivity by, for example, examining whether clouds are being properly treated and why seemingly similar models are giving different estimates of the latitudinal and regional change in temperature and precipitation.

Thus, present rates of increase of greenhouse gas emissions, present model results, and observations yield a range of possible future warming rates and ultimate warming that is uncomfortably large. Reducing uncertainties regarding the rate of climatic change is particularly important.

What is the Environmental and Societal Significance of the Climatic Changes?

Discussion of the potential agricultural, environmental, and societal significance of the projected climatic changes is necessarily more speculative than of potential climatic changes, because the needed analyses are more complex, understanding and models are less advanced, and, therefore, the preliminary results are more subject to personal interpretation. The following analysis represents my personal interpretation.

As a starting point, fossil fuels and many of the trace gases provide tremendous societal benefits. If there is to be consideration given to regulatory or other actions, it would seem to me that potential impacts must be of comparable magnitude to foregone benefits. Although significantly more information is needed to permit a thorough analysis, there are several areas related to societal activities for which the potential for large impacts may exist.

Human Health : The direct health effects of a doubled CO_2 concentration are not believed to be great — the concentration in conference rooms often exceeds expected levels and the acceptable occupational levels are roughly an order of magnitude higher than the range of concentrations now experienced by the general public. The health effects of the climatic changes may be more significant because of the potential for increased frequency of extremely hot days, higher survival rates of pests, and increased prevalence of tropical diseases. Chemical changes in atmospheric ozone may also increase ultraviolet radiation and reduce air quality at the surface. Although very large health impacts have not yet been demonstrated, small health-related consequences to a very large number of people could yield a very large impact.

Food and Fiber Resources : For some plants, increased CO_2 can enhance growth and reduce evapotranspiration losses [12]; some of these species, however, are nuisance plants or weeds. In middle and high latitudes, growing seasons would become longer. There are indications that earlier drying of the soils may occur, which may require more irrigation and greater soil conservation efforts. On balance, technologically advanced countries seem likely to be able to adapt (climate being only one factor affecting agricultural production), but in my opinion, peoples tied to traditional agricultural practices may be seriously impacted.

Natural Ecosystems : A changing climate and CO_2 concentration will change the competitive stresses between species and between plants and pests. Little, however, is actually known about the significance of the responses. There is a great need for more research on stress ecology.

Fresh Water Resources : The shifting seasonal and regional patterns of precipitation, a rising snowline, and increased evaporation could reduce the availability of fresh water resources and cause dislocations in water storage capabilities. Both changes could stress agriculture and reduce water quality. This is a potentially very important impact to which it might be very hard to adapt, and significant improvements in climate and resource models are needed to permit more careful evaluation.

Marine Ecosystems : Changing oceanic chemistry and circulation patterns could stress marine food resources, but again little is known.

Sea Level : Perhaps the most publicized potential effect of global warming is sea level rise, in large part because amelioration could be exceedingly costly. The melting of land ice (both mountain and polar glaciers) and the thermal expansion of ocean waters could each contribute to a rise in sea level of tens of centimeters or more during the next century. Although land subsidence and rebound can be large contributors to local changes in sea level, observations suggest that sea level has risen by 5–15 cm over the past hundred years [13]. Surveys of mountain glaciers suggest that their retreat has contributed about 5 cm to this rise, with Greenland about in balance and the Antarctic ice sheet perhaps slightly increasing in mass. The effect of climate change on the Antarctic ice cap is complex and uncertain; (for modest warmings, the increase in snowfall will likely exceed any increase in melting; at some unknown point, however, we may become committed to catastrophic collapse, even if such an event is unlikely to begin for a few centuries). For the high-sensitivity climate models to be correct, injection of heat into the deep ocean would be causing substantial thermal expansion and sea level rise that can be consistent with observations only if substantial Antarctic build-up is occurring. Thus, satellite topographic measurements of the Antarctic are needed to help us determine whether the climate is as sensitive to greenhouse effects as present models suggest. Because a significant sea level rise could have large impacts on seashores and urban areas, expanded research efforts are needed.

Can and Should Anything Be Done Now?

The sum of the potential impacts, especially if viewed in terms of a stagnant view of society and its technologies, would almost surely be very large. Some voices are already being raised voicing great concern. But society is not stagnant, so such an analysis may overestimate at least some of the potential consequences and may miss others. Attempting to project impacts 50 to 75 years ahead in a changing and adapting society is, at the least, extremely uncertain, and at worst, impossible to harmful. Thus, in considering steps to take, a prudent strategy would seem to be to (1) initiate steps to minimize the rate of climate change, especially when also justified on other grounds, (2) investigate potential actions that may be able to help ameliorate projected impacts, (3) realize that at least some adaptation will be essential, and planning to promote such adaptation may greatly reduce potential negative impacts, and (4) significantly increase research in order to reduce uncertainties and explore possibilities.

Prevention of releases of greenhouse gases by, for example, conservation, increased use of non-fossil fuel energy resources, and minimizing release of materials such as chlorofluorocarbons, could help reduce the rate of climate change, thereby perhaps making easier whatever adaptations may be necessary. Almost certainly, the societal disruptions of stopping all emissions of all greenhouse gases would prove unacceptable, and, given that we are not now at equilibrium, even a complete halt to emissions would fail to halt continuing climate change. But reducing emissions can help; however, it will require international cooperation to amplify the limited benefits of any nation's unilateral efforts.

Ameliorative actions, for example, improving abilities to modify the climate (e.g., seeding hurricanes if their frequency were to increase or injecting sulfates into the stratosphere to reflect solar radiation and counter the warming tendency), are extremely difficult to design may produce contrary or undesired effects, and may have varying regional effects that would make international agreement on appropriate actions difficult.

For those economic aspects that have relatively short adaptation times (e.g., crop-switching), the normal technologically and economically induced evolution may occur more rapidly than the climate changes, and adaptation can occur relatively easily. But for many other societal aspects (e.g., hydroelectric facilities, power plants, infrastructure), much more accurate knowledge of potential changes is needed to help in optimizing and planning for the needed capital and infrastructure changes. Sea level rise and water resource changes probably pose the most difficult potential impacts with which society would have to deal.

There is no doubt that the presence of infrared-absorbing gases in the atmosphere warms the surface (the "greenhouse" effect). Accelerated research is needed to reduce important uncertainties about the magnitude and rate of climatic change in various locations and seasons if the concentrations of these gases change. In the short-term perspective that characterizes much of society, the climatic changes will occur gradually enough that other factors will likely dominate societal attention. But the CO_2-induced effects are cumulative, unlike the normal climatic variability that is now the major atmospheric concern (e.g., droughts, floods, etc.). Thus, the potential exists for sea level to keep rising, breaching or bypassing the dikes that can be extended only so far, and for water resources to become more scarce, eventually forcing abandonment of agriculture in some regions and the construction of new dams or lengthy aqueducts in others.

Although we may not now know enough about potential greenhouse effects, we should not ignore or minimize the potential for significant impacts. Rather, we should invest the effort to improve understanding and identify ways to prepare for and respond to the changes that may occur, especially because the uncertainties concerning physical effects and society's ability to adapt can work in both directions. For now, better information is the key to being better prepared and deciding how best to proceed.

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References

1. Revelle, R., Broecker, W., Craig, H., Keeling, C.D. and Smagorinsky, J., Atmospheric Carbon Dioxide. Appendix Y4 in: Restoring the Quality of the Environment, Report of the Environmental Pollution Panel of the President's Science Advisory Committee, 1965.
2. Kutzbach, J.E., and Guetter, P.J., J. Atmos. Sci., in press, 43.
3. National Research Council (NRC), Changing Climate, Washington, DC, Carbon Dioxide Assessment Committee, National Academy Press, 1983.
4. MacCracken, M.C. and Luther, F.M. (eds), Projecting the Climatic Effects of Increasing Carbon Dioxide, Washington, DC, Department of Energy (DOE), DOE/ER-0237, 1985a.
5. World Climate Programme (WCP), Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, Geneva, Switzerland, International Council of Scientific Unions/United Nations Environment Programme/World Meteorological Organization, WMO-No. 661, 1986.
6. Dickinson, R.E., and Cicerone, R.J., Nature, 1986, 319, 109–115.
7. Wang, W.-C., Wuebbles, D.J., Washington, W.M., Isaacs, R.G. and Molnar, G., Rev. of Geophys., 1986, 24, 110–140.
8. MacCracken, M.C. and Luther, F.M. (eds.), Detecting the Climatic Effects of Increasing Carbon Dioxide, Washington, DC, Department of Energy (DOE), DOE/ER-0235, 1985b.
9. Trabalka, J. (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, Washington, DC, Department of Energy (DOE), DOE/ER-0239, 1985c.
10. Hoffert, M.I., and Flannery, B.P., submitted to Science, 1986.
11. Wigley, T.M.L., and Schlesinger, M.E., Nature, 1985, 315, 649–652.

12. Strain, B.R. and Cure, J.D. (eds.), Direct Effects of Carbon Dioxide on Vegetation, Washington, DC, Department of Energy (DOE), DOE/ER-0238, 1985d.

13. Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climatic Change, Washington, DC, National Research Council (NRC), Polar Research Board, National Academy Press, 1985.